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Systematic review of the acute and chronic effects of high-intensity interval training on executive function across the lifespan

Shu-Shih Hsieh^a, Ting-Yu Chueh^b, Chung-Ju Huang^c, Shih-Chun Kao^d, Charles H. Hillman^{a,e}, Yu-Kai Chang^{b,f} and Tsung-Min Hung^{b,f}

^aDepartment of Psychology, Northeastern University, Boston, MA, USA; ^bDepartment of Physical Education, National Taiwan Normal University, Taipei, Taiwan; ^cGraduate Institute of Sport Pedagogy, University of Taipei, Taipei, Taiwan; ^dDepartment of Health and Kinesiology, Purdue University, West Lafayette, IN, USA; ^eDepartment of Physical Therapy, Movement, and Rehabilitation Science, Northeastern University, Boston, MA, USA; ^fInstitute for Research Excellence and Learning Science, National Taiwan Normal University, Taipei, Taiwan

ABSTRACT

Research regarding the effects of high-intensity interval training (HIIT) on executive function has grown exponentially in recent years. However, there has been no comprehensive review of the current state of literature. Therefore, the aim of this systematic review is to summarize previous research regarding the acute and chronic effects of HIIT on executive function across the lifespan and highlight future research directions. The results indicated that acute bouts of HIIT has a positive effect on inhibition in children/adolescents and adults, and further that chronic HIIT benefits inhibition and working memory in children. More research employing chronic interventions, focusing on middle-aged and older adults, and examining the effects on the working memory and cognitive flexibility domains of executive function are needed. Future research should also focus on a) the use of stronger research designs, b) the effects of HIIT dosage/modality, c) consideration of individual differences, d) possible underlying mechanisms, and e) examining the feasibility of translating HIIT to real-world settings.

ARTICLE HISTORY

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KEYWORDS

High-intensity exercise;
intermittent exercise;
inhibition; lactate

1. Introduction

A growing body of evidence indicates a positive association of physical activity with cognition and brain function across the lifespan (Hillman et al., 2008; Kao et al., 2020). The current literature supports the positive influence of acute and chronic moderate-intensity, continuous aerobic exercise (Chang et al., 2012; Guiney & Machado, 2013; Kamijo et al., 2009; Li et al., 2017; McMorris et al., 2011) and resistance exercise (De Asteasu et al., 2017; Soga et al., 2018; Wilke et al., 2019) on cognitive function across different age groups. In addition, recent findings have bolstered the cognitive benefits associated with high-intensity interval training (HIIT) (Cooper, Dring et al., 2016).

HIIT refers to physical activity characterized by relatively brief bursts of vigorous activity (i.e., ~90% of maximal aerobic power for brief intervals), interspersed by short periods of rest or low-intensity physical activity for recovery (Eddolls et al., 2017). It has been suggested that HIIT, typically studied using treadmill running or cycling on an ergometer (Eddolls et al., 2017), may be an attractive alternative to traditional moderate-intensity continuous exercise or resistance exercise as a means of promoting various health outcomes, such as aerobic capacity (Lee, Hsu et al., 2018), lipid metabolism (Lee, Kuo et al., 2018), vascular function (O'Brien et al., 2020), and balance (Jiménez-García et al., 2019). Although HIIT may be associated with higher risk of injury (Rynecki et al., 2019), its health-related benefits can be manifested once implemented appropriately. Moreover, the time-efficient nature of HIIT has made it a

desirable option in overcoming “lack of time” – one of the most cited barriers to engaging in physical activity (Centers for Disease Control and Prevention, 2012).

Despite emerging evidence supporting the efficacy and feasibility of HIIT for improving cognitive and brain health, to date there is only one narrative review included only three studies (Cooper, Bandelow et al., 2016). The review did not provide explicit information on either the nature of the HIIT protocols or details of the cognitive assessments used in the studies (Cooper, Bandelow et al., 2016), and only focused on young adults (Cooper, Bandelow et al., 2016). Considering the rapid growth of this line of research, it is necessary to provide an updated review that summarizes the existing literature in a more comprehensive manner.

The aim of this paper is to systematically summarize the current state of the literature regarding the effects of HIIT on executive function, the most commonly studied aspect of cognition. Given that the literature has indicated cognitive benefits stemming from physical activity across the lifespan (De Asteasu et al., 2017; Chang et al., 2012; Guiney & Machado, 2013; Hillman et al., 2008; Kamijo et al., 2009; Kao et al., 2020; Li et al., 2017; McMorris et al., 2011; Soga et al., 2018; Wilke et al., 2019), we categorized studies into children/adolescents, young adults, and older adults. Moreover, though restrictive, we exclusively focused on the effects of HIIT on executive function, a subdomain of cognition involving top-down, multifaceted process underlying goal-oriented behaviour (Diamond, 2013). Our

emphasis was motivated by two reasons. First, executive function is a central component of cognition known to influence many cognitive processes, which are ecologically relevant to various domains of daily living, including academic achievement (Wang et al., 2015; Wang & Gathercole, 2013, 2015), vocational performance (Bailey, 2007), and quality of life (Davis et al., 2010). Second, there is a robust conceptual link between physical activity and executive function across the lifespan (Hillman et al., 2008; Kao et al., 2020), and extension from traditional aerobic/resistance exercise to HIIT is theoretical-driven. For example, acute bouts of HIIT may facilitate executive function via increased levels of circulating lactate, a biomarker that is essential for neural metabolism and neuronal excitability in the brain (Magistretti & Allaman, 2018). Other studies indicate that acute HIIT may benefit executive function via a more efficient neuroelectric activation and faster stimulus processing (Kao et al., 2017, 2018) or higher levels of cerebral oxygenation in the prefrontal cortex (Lambrick et al., 2016). Moreover, chronic HIIT may facilitate executive function via decrease in inflammation-related cytokines (Freitas et al., 2018), increased expression of BDNF (Freitas et al., 2018), and increased uptake of glucose (Robinson et al., 2018). Collectively, our goal is that the current review may serve as a reference which guides future research understanding the effectiveness of acute and chronic HIIT on executive function.

2. Methods

2.1. Search strategy

The current review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, Moher et al., 2009) for literature search and selection. The literature search was performed using three electronic databases, PubMed, Web of Science, and Scopus. While no start date was specified, the search was completed on February 2020 and therefore only included studies published as of that time. The search terms “*high-intensity exercise*”, “*intermittent exercise*”, “*interval exercise*”, and “*sprint*” were grouped using the connector “OR” and then were combined using the connector “AND” with search terms “*cognition*”, “*cognitive function*”, “*cognitive performance*”, and “*executive function*”, resulting in the following search query: ((“*high-intensity exercise*” OR “*intermittent exercise*” OR “*interval exercise*” OR “*sprint*”) AND (“*cognition*” OR “*cognitive function*” OR “*cognitive performance*” OR “*executive function*”)).

2.2. Eligibility criteria

Articles were considered eligible if they met all of the following criteria: a) the research involved an intervention study, either acute (single bouts of HIIT) or chronic (repeated bouts of HIIT over days, weeks, or months), where details were given about the nature of the HIIT studied (e.g., the type of movements involved, intensity, number of sessions, duration of each session, duration of recovery between sessions, work-to-recovery ratio (WRR)); b) the reported high intensities were either >80% heart rate reserve (HR_{reserve}), >85% heart rate maximal (HR_{max}), >90%

maximal oxygen consumption ($VO_{2\text{max}}$) or peak power output (Eddolls et al., 2017); c) the research focused on different subcomponents of executive function based on the definitions from Diamond (2013): inhibition (i.e., the ability to selectively focus on task-relevant information while resisting attention to a prepotent but undesirable response), working memory (i.e., the ability to hold information in mind and mentally work with it or with information no longer perceptually presented), and cognitive flexibility (i.e., the ability to flexibly change mental representations back and forth between two task demands); d) outcome measures involved executive function-related tasks with explicitly defined performance indices (e.g., response accuracy, response times, items recalled), and executive function-related tasks were identified by referring to the studies from Diamond (2013) and Etnier and Chang (2009); e) participants were healthy individuals without diagnosed disease or disorders; and e) the research was published in English.

2.3. Study selection

The screening and selection of studies were completed by two of the authors (SSH and TYC) on February 2020. First, titles and abstracts were examined to identify studies that met inclusion criteria after removal of duplicates. Second, the full text of eligible studies based on the screened studies was read to determine their final inclusion. Disagreement between the two reviewers was resolved by a consensus meeting with experts in the field (YKC and TMH) on February 2020. Finally, articles including acute and chronic HIIT interventions and executive function-related tasks were reviewed. Figure 1 provides an overview of the selection process.

2.4. Assessment of risk of bias

Two authors (SSH and TYC) assessed the study quality according to the PEDro scale (Maher et al., 2008). Both reviewers had undergone the PEDro training programme. Any disagreements were discussed with a third reviewer (TMH) until a consensus was achieved. It should be noted that the original version of the PEDro scale was modified to better fulfill the purpose of this systematic review. That is, blinding of participants and researchers were not considered for quality assessment for studies with acute exercise settings (Ludyga et al., 2016). These criteria were disregarded because true blinding could not be accomplished in studies with acute exercise settings. The summary of the quality assessment was presented in Figure 2 and Supplement 1.

2.5. Data extraction process

The final studies were examined thoroughly, and the following data were extracted: (1) first authors' name, publication year, country of data collection; (2) sample size, participants' age; (3) study design and/or group assignment; (4) details about HIIT intervention; (5) subcomponents of executive function assessed and its assessment paradigm; and (6) main outcomes.

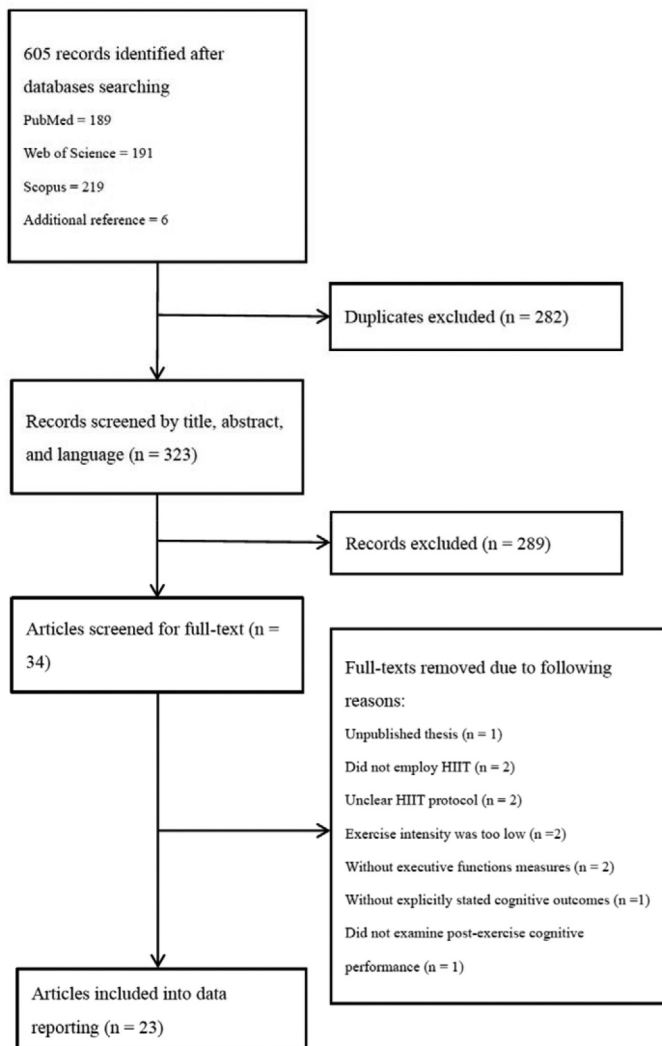


Figure 1. Diagram of study selection following PRISMA guidelines.

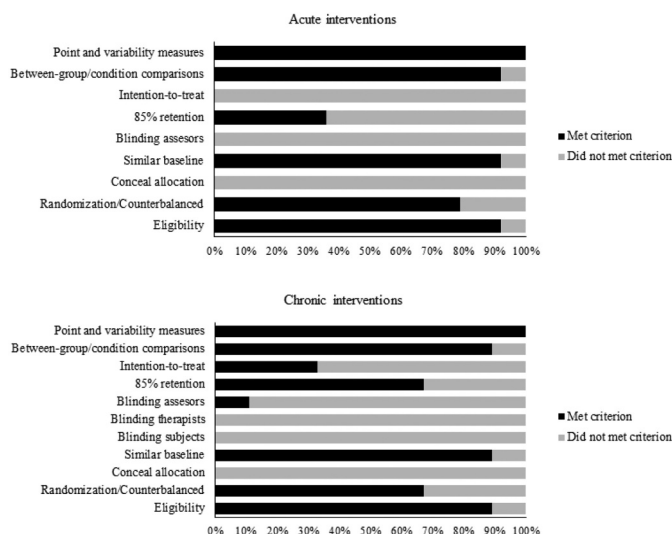


Figure 2. Results of risk of bias analysis.

3. Results

3.1. Study selection

A total of 605 studies were initially identified from PubMed, Web of Science, and Scopus. Of these, 282 duplicates were removed. Accordingly, a total of 323 articles were screened for title and abstract. After the first stage of screening, 34 articles were selected for full-text screening, and resulted in a total of 23 full-text articles included in the data extraction and reporting. The flow diagram of the study selection process following PRISMA guidelines is shown in Figure 1. Also see Tables 1 and 2 for summary of study characteristics and results (all studies in Tables 1 and 2 are numbered for better referencing in the results section).

3.2. Description of studies reviewed

The literature search yielded a total of 23 studies published between February 2014 and January 2020. Studies took place in Europe (Ref 1, 2, 3, 7, 8, 10, 13, 14, 23), North America (Ref 9, 12, 15, 18, 20), South America (Ref 17), Asia (Ref 4, 11, 16), Oceania (Ref 5, 6, 19, 21), and South Africa (Ref 22). These investigations included sample sizes from 6 to 64 participants, ranging in age between 9 and 16 years for children and adolescents (26%, $n = 6$) (Ref 1–6), and between 19 and >70 years for adults (74%, $n = 17$) (Ref 7–23).

With regards to study design, 26% ($n = 6$) of studies examined chronic effects of HIIT using a randomized controlled trial (RCT) design (Ref 5, 6, 19, 21–23), while 13% ($n = 3$) of studies investigated the chronic effects of HIIT with either a non-randomized design (Ref 4, 18) or a within-group, pre-test-post-test design (Ref 20). Alternatively, 43% ($n = 10$) of studies investigated the acute effects of HIIT using a within-subjects, crossover design (Ref 2, 3, 9–12, 13, 15–17), and 17% ($n = 4$) of studies investigated the acute effects of HIIT with either a between-subjects design (Ref 1, 7, 8) or a within-subjects, pre-test-post-test design (Ref 14).

Regarding the modality of HIIT, 78% ($n = 18$) of studies (Ref 2, 3, 5, 7–13, 15–18, 20–23) employed traditional HIIT, in terms of cycling or running/sprinting, whereas the other 22% ($n = 5$) (Ref 1, 4, 6, 14, 19) adopted high-intensity functional circuit training (HICT) that consisted of functional, multi-joint movements via both aerobic and muscle-strengthening exercises (Eddolls et al., 2017).

Relative to the different subcomponents of executive function, 70% ($n = 16$) of studies focused on inhibition (Ref 1–3, 5, 7, 8, 11–18, 21, 22), 35% ($n = 8$) of studies tapped working memory (Ref 2, 4, 5, 14, 17, 20, 22, 23), and 22% ($n = 5$) of studies targeted cognitive flexibility (Ref 6–8, 10, 19). Table 3 demonstrates paradigms employed to assess different subcomponents of executive function. In the following sections, findings from the literature are summarized by age category.

3.3. HIIT in children and adolescents

3.3.1. Acute interventions

Of the 23 studies reviewed, 13% ($n = 3$) focused on the acute effects of HIIT on executive function in children and adolescents (Ref 1–3) (see Table 1 for details of studies), yielding a total of 5 intervention effects (Figure 3). All three studies demonstrated a positive effect of acute HIIT on inhibition.

Table 1. Summary table of studies on children/adolescents.

Authors, country	Design	Participants	Intervention	Measures	Outcomes
Acute intervention (n = 3)					
[1] Ludyga et al. (2018) Switzerland	Between-subjects Higher-volume (HV) vs. lower-volume (LV) vs. CON	HV N = 32 Age = 14 ± 1 yrs LV N = 34 Age = 14 ± 1 yrs CON N = 28 Age = 14 ± 1 yrs N = 44 (21 boys) Age: 13 ± 1 yrs	M: Circuit training (i.e., jumping jacks, shuttle run, rope skipping, bench stepping, sideway jumps, dribbling while running) *total exercise time: 16 min I: maximal W/R: HV: 1 min/30 sec (passive); LV: 30 sec/30 sec (passive)	Flanker (inhibition)	(-) Flanker: HV (+) Flanker: LV *LF effect sustained for 60 minutes post-exercise
[2] Cooper, Bandelow et al., 2016 United Kingdom	Crossover HIIT vs. CON	N = 20 (9 boys) Age: 9 ± 1 yrs	M: running (sprint) I: maximal S: 10 W/R: 10 sec/50 sec (active)	Stroop (inhibition) Corsi block (WM)	(+) Stroop (-) Corsi block
[3] Lambrick et al. (2016) United Kingdom	Crossover HIIT vs. CAE	N = 20 (9 boys) Age: 9 ± 1 yrs	M: running I: moderate: 90% GET; intermediate: 40% VO _{2peak} GET; vigorous: maximal exertion S: 6 W/R: 1.5 min/1 min (active) *exercise consisted of 33 sec moderate, 45 sec intermediate, 10 sec vigorous running)	Stroop (inhibition)	(+) Stroop *effect sustained for 30 minutes post-exercise
Chronic intervention (n = 3)					
[4] Tottori et al. (2019) Japan	Non-randomized HIIT vs. CON	HIIT N = 27 (17 boys) Age: 10 ± 1 yrs CON n = 29 (14 boys) Age: 10 ± 1 yrs	4 weeks 3 sessions/week M: HIIT (i.e., shuttle runs, jumping jacks, vertical jumps, mountain climbers, and plank in and out jumps) I: 85% HR _{max} W/R: 30 sec/30 sec	Digit span backward (WM)	(+) Digit span backward
[5] Moreau et al. (2017) New Zealand	RCT HIIT vs. CON	HIIT N = 152 (62 boys) Age: 10 ± 2 yrs CON n = 153 (56 boys) Age: 10 ± 2 yrs	6 weeks 5 session/week M: sprint I: maximal S: 5 W/R: 20 sec/20 sec – 20 sec/60 sec	Go/no go test, Stroop test, Flanker (inhibition) N-back, Digit span backward, Corsi block (WM)	(+) Go/no go test (+) Stroop (+) Flanker (+) N-back (+) Digit span backward (+) Corsi block *size of effect: BDNFmet66 carriers > non-carriers (-) TMT-B: aerobic-based (-) TMT-B: aerobic- and muscular-based
[6] Costigan et al. (2016) Australia	RCT Aerobic-based HICT vs. Aerobic- and muscular-based HICT vs. CON	Aerobic-based HICT N = 21 Age: 16 ± 1 yrs Aerobic- and muscular-based HICT N = 22 Age: 16 ± 1 yrs CON N = 22 Age: 16 ± 1 yrs	8 weeks 3 sessions/week M: Aerobic-based HICT- shuttle runs, jumping jacks, skipping; aerobic- and muscular-based HICT- shuttle runs, jumping jacks, skipping, squats, stepping lunge, push-ups *total exercise time: 8–10 min (wk 1–3: 8 min; wk 4–6: 9 min; wk 7–8: 10 min) I: maximal W/R: 30 sec/30 sec	TMT-B (CF)	

Note. M: modality. I: intensity. S: number of sets. W/R: work-to-recovery ratio. HIIE: high-intensity interval exercise. HIIT: high-intensity interval training. HICT: high-intensity functional training. CAE: continues aerobic exercise. CON: control condition/group. WM: working memory. CF: cognitive flexibility. TMT-B: trail-making test B

Table 2. Summary table of studies on adults.

Authors, country	Design	Participants	Intervention	Measures	Outcomes
<i>Acute intervention (n = 11)</i>					
[7] Kujach et al. (2020) Poland	Between-subjects HIIT vs. CON	HIIT N = 20 (20 men) Age: 21 ± 1 yrs CON N = 16 (16 men) Age: 22 ± 1 yrs	M: Cycling (ergometer) I: > 100% $\dot{V}O_{2max}$ S: 6 W/R: 30 sec/4.5 min (passive)	Stroop (inhibition) TMT-B (CF)	(↑) Stroop (↑) TMT-B
[8] Schwarck et al. (2019) Germany	Between-subjects HIIT vs. CAE vs. CON	HIIT N = 13 (13 men) Age: 24 ± 4 yrs CAE N = 13 (13 men) Age: 24 ± 3 yrs CON N = 13 (13 men) Age: 23 ± 3 yrs	M: Running (treadmill) I: 90% $\dot{V}O_{2max}$ S: 5 W/R: 2 min/3 min (active)	Stroop (inhibition) TMT-B (CF)	(-) Stroop (-) TMT-B
[9] Miller et al., 2018 United States	Crossover Moderate-volume HIIT (MV) vs. Low-volume HIIT (LV)	N = 25 (12 men) Age: 23 ± 3 yrs	M: Cycling (ergometer) I: 85% HR_{max} S: 10 sets for MV, 5 sets for LV W/R: 1 min/1 min (active)	Stroop (inhibition)	(↑) Stroop: MV (↑) Stroop: LV *no difference between MV and LV
[10] Dupuy et al. (2018) France	Crossover high-intensity (HI) vs. moderate-intensity (MI) vs. CON	N = 17 (17 men) Age: 28 ± 5 yrs	M: Cycling (ergometer) I: 95% PPO (HI); 60% PPO (MI) S: 6 W/R: 3 min/3 min (passive) M: Cycling (ergometer) I: 80–90% W_{max} S: 4 W/R: 4 min/3 min (active) M: Running (treadmill) I: 90% HR_{max} S: 8 W/R: 1 min/1 min (active) M: Cycling (ergometer) I: $P_{VT2} + 25\% P_{max} - P_{VT2}$ S: 4 W/R: 3 min/3 min (active)	Modified Stroop (CF) Stroop (inhibition) Flanker (inhibition) Flanker (inhibition)	(↑) Modified Stroop: HI (↑) Stroop (↑) Flanker
[11] Hashimoto et al. (2018) Japan	Crossover HIIT vs. CAE	N = 14 (14 men) Age: 24 ± 1 yrs			
[12] Kao et al. (2018) United States	Crossover HIIT vs. CAE vs. CON	N = 36 (18 men) Age: 22 ± 3 yrs			
[13] Ligeza et al. (2018) Poland	Crossover HIIT vs. CAE vs. CON	N = 18 (18 men) Age: 25 ± 2 yrs			(-) Flanker

(Continued)

Table 2. (Continued).

Authors, country	Design	Participants	Intervention	Measures	Outcomes
[14] Gniat et al. (2017) Poland	Within-subjects, pre-post design *two age groups: young and middle-aged groups	Young N = 8 (8 women) Age: 20 ± 4 yrs Middle-aged N = 6 (6 women) Age: 41 ± 7 yrs N = 64 (27 men)	M: circuit training (i.e., jumping jacks, push-ups, abdominal crunch, squat, plank, triceps dip on chair, high-knee running, lunge, push-ups with rotations, side plank) *total exercise time: 3 × 7 min/circuit I: maximal effort W/R: 30 sec/10 sec (passive)	Stroop (inhibition) Corsi block (WM)	Young (↑) Corsi block (-) Stroop: young Middle-aged (↑) Corsi block (-) Stroop: middle-aged
[15] Kao et al. (2017) United States	Crossover HIIT vs. CAE vs. CON	N = 64 (27 men) Age: 19 ± 1 yrs N = 12 (12 men) Age: 23 ± 1 yrs N = 22 (9 men) Age: 54 ± 5 yrs	M: Running (treadmill) I: 90% HR _{max} S: 3 W/R: 1.5 min/1 min (active) M: Cycling (ergometer) I: 90% VO _{2peak} S: 4 W/R: 4 min/3 min (active) M: Cycling (ergometer) I: 80% HR _{reserve} S: 10 W/R: 1 min/1 min (active)	Flanker (inhibition) Stroop (inhibition)	(↑) Flanker (↑) Stroop: HIIT
[16] Tsukamoto et al. (2016) Japan	Crossover HIIT vs CAE	N = 22 (9 men)		Stroop (inhibition) Digit span (WM)	(↑) Stroop (-) Digit span
[17] Alves et al. (2014) Brazil	Crossover HIIT vs CON	N = 23 (8 men)		Flanker (inhibition) Go/no-go (inhibition)	(-) Flanker (-) Go/no-go
<i>Chronic intervention (n = 6)</i> [18] Kovacevic et al. (2020) Canada	Non-randomized HIIT vs. CAE vs. CON	HIIT N = 21 (7 men) Age: 72 ± 4 yrs CAE N = 20 (10 men) Age: 72 ± 6 yrs CON N = 23 (8 men) Age: 72 ± 7 yrs HIIT N = 22 (8 men) Age: 20 ± 2 yrs CON N = 31 (10 men) Age: 21 ± 2 yrs	12 weeks 3 sessions/week M: Running (Treadmill) I: 90–95% HR _{max} S: 4 W/R: 4 min/3 min (active)	TMT-B (CF)	(-) TMT-B
[19] Eather et al. (2019) Australia	RCT HICT vs. CON		8 weeks 3 sessions/week M: varied combinations of aerobic (e.g., shuttles, skips, bear walks) and core resistance (e.g., push-ups, squats, sit ups) exercises using either body weight or basic equipment (e.g., sports balls or 2 kg medicine balls), with a variety of programs were made available for participants to choose (i.e., Sport HIIT, Gym HIIT, Combat HIIT, and Brain HIIT). Each themed session involved adaptations of the basic exercise combination (e.g., Combat HIIT included squat kicks and squat punches, Brain HIIT included shuttle runs while answering questions, and Sport HIIT used shuttle style basketball dribbling as an aerobic task) *total exercise time: 8 min (week 1–4), 10 min (week 5–6), and 12 min (week 7–8) I: 85% HR _{max} W/R: 30 sec/30 sec (passive)		

(Continued)

Table 2. (Continued).

Authors, country	Design	Participants	Intervention	Measures	Outcomes
[20] Nicolini et al. (2019) Canada	Within-group pre-post design	N = 18 (18 men) Age: 23 ± 4 yrs	6 weeks 3 sessions/week M: Cycling (Ergometer) I: 105–135% PPO S: 5 W/R: 1 min/1.5 min (active) 2 weeks 3 sessions/week M: Cycling (ergometer) I: 90%HR _{max} S: 6 W/R: 30 sec/4 min (first week) to 30 sec/3 min (second week)	OSPAN (working memory)	(-) OSPAN
[21] De Sousa et al. (2018) Australia	RCT High-fidelity (HF) vs. low-fidelity (LF) vs. CON *HF/LF was determined by whether in-exercise HR >90% HR _{max}	HF N = 26 (12 men) Age: 23 ± 4 yrs LF N = 46 (25 men) Age: 24 ± 6 yrs CON N = 19 (10 men) Age: 25 ± 4 yrs		Flanker (inhibition)	(↑) Flanker: HF (↑) Flanker: LF *size of effect: HF > LF
[22] Coetsee and Terblanche (2017) South Africa	RCT HIIT vs. CAE vs. RT vs. CON	HIIT N = 13 (3 men) Age: 64 ± 6 yrs CAE N = 13 (3 men) Age: 62 ± 6 yrs RT N = 22 (7 men) Age: 62 ± 5 yrs CON N = 19 (8 men) Age: 63 ± 6 yrs	16 weeks 3 sessions/week M: Running I: 90–95% HR _{max} S: 4 W/R: 4 min/3 min (active)	Stroop	(Inhibition)
(-) Stroop: HIIT [23] Connolly et al. (2017) United Kingdom	RCT HIIT vs. CAE vs. CON	HIIT N = 15 Age: 44 ± 7 yrs CAE N = 15 Age: 43 ± 7 yrs CON N = 19 Age: 45 ± 7 yrs	12 weeks 2 sessions/week M: Cycling (ergometer) I: 30 sec low-intensity (~30% of maximum effort), 20 sec moderate-intensity (~50–60% of maximum effort) and 10 sec high-intensity (>90% maximum effort) S: 5 W/R: 5 min/2 min (passive)	N-back (WM)	(↑) N-back: HIIT

Note: M: modality. I: intensity. S: number of sets. W/R: work-to-recovery ratio. HIIT: high-intensity interval training. HICT: high-intensity circuit training. CAE: continues aerobic exercise. CON: control condition/group. WM: working memory. CF: cognitive flexibility. PPO: peak power output. OSPAN: operation span task.

Table 3. Cognitive paradigms used to examine executive functions.

Inhibition	Working memory	Cognitive flexibility
Stroop (n = 11)	N-back (n = 2)	Trail-making test B (n = 4)
Flanker (n = 7)	Digit span backward (n = 3)	Modified Stroop (n = 1)
Go/no-go (n = 2)	Corsi block tapping test (n = 3)	
	Operation span (n = 1)	

Specifically, two studies found positive effects of acute HIIT on inhibition (Ref 2, 3), with the effect sustained for ~30 minutes following exercise cessation (Ref 3). Likewise, one study found positive effect of acute HICT on inhibition, with the beneficial effect sustained for ~60 minutes (Ref 1). Notably, data from one study revealed that HICT with a work-to-recovery ratio (WRR) of 1:1 (i.e., 30-second exercise: 30-second recovery) resulted in improved inhibition performance whereas HICT with a WRR of 2:1 (i.e., 60-second exercise: 30-second recovery) resulted in non-significant effect (Ref 1). In the case of other subcomponents of executive function, one study found a null effect of acute HIIT on working memory in children (Ref 2).

3.3.2. Chronic interventions

Among the 23 studies retrieved, 13% (n = 3) involved chronic HIIT interventions in children and adolescents (Ref 4–6) (see Table 1 for details) and yielded a total of 9 intervention effects (Figure 3). One study found improved performance for inhibition and working memory measured via six different executive function tasks (i.e., go/no-go task, flanker task, Stroop test, N-back, digit span backward test, Corsi block tapping test) following a HIIT program in children (Ref 5). Another study found positive effect of HICT on working memory in children (Ref 4). As for cognitive flexibility, one study found null effect from both an aerobic-based HICT and an aerobic + muscular-based HICT after training in adolescents (Ref 6). However, cognitive gains following a HIIT program were moderated by the genotype of brain-derived neurotrophic factor (BDNF), with BDNF^{met66} carriers demonstrating larger cognitive gains relative to non-carriers following training (Ref 5).

3.4. HIIT in adults

3.4.1. Acute interventions

Of the 23 studies retrieved, 43% (n = 10) (Ref 7–9, 11–17) investigated the acute effects of HIIT on inhibition in adults (see Table 2 for details), with a total of 18 intervention effects (Figure 3). Of these 10 studies, seven of them supported the positive effect of acute HIIT in young (Ref 7, 9, 11, 12, 15, 16) and middle-aged adults (Ref 17), whereas three others found no influence of acute HIIT in young (Ref 8, 13, 14) and middle-aged adults (Ref 14). For working memory, studies found positive effect of a single bout of HIIT in young adults (Ref 14) but not in middle-aged adults (Ref 14, 17). In terms of cognitive flexibility, two studies support the positive effect of an acute bout of HIIT (Ref 7, 10) whereas one study found no benefit (Ref 8).

3.4.2. Chronic interventions

Of the 23 studies retrieved, 26% (n = 6) implemented chronic HIIT with young (Ref 19–21), middle-aged (Ref 23), and older adults (Ref 18, 22) (Table 1 for details), generating a total of 7 intervention effects (Figure 3). Studies reported the positive effect of HIIT on inhibition in young adults (Ref 21) but not in older adults >60 years of age (Ref 18, 22). Alternatively, three studies found that whereas HIIT benefited working memory in older adults (Ref 23), there was no beneficial effect on young adults' working memory (Ref 20) or cognitive flexibility (Ref 19). However, one study found young adults with higher compliance to the HIIT protocol (peak HR during exercise: 184.2 beats.min⁻¹) had larger improvement in inhibition performance following training relative to those with lower compliance (170.5 beats.min⁻¹) (Ref 21).

4. Discussion

4.1. Summary of the search results

The current systematic review summarizes evidence from studies examining the acute and chronic effects of HIIT as they relate to different subcomponents of executive function. Most studies included in this review were deemed fair quality based on criteria established in the PEDro scale (Maher et al., 2008) (Figure 2 and Supplement 1). Overall, the current state of the literature favours a positive effect of acute HIIT on inhibition in children/adolescents and adults as well as a beneficial effect of chronic HIIT on inhibition and working memory in children.

4.2. Effects of HIIT on children and adolescents

The findings on children and adolescents support a positive effect of acute HIIT on inhibition, with the benefits sustain 30 to 60 minutes following intervention (Lambrick et al., 2016; Ludyga et al., 2018), whereas it remains unclear if acute bouts

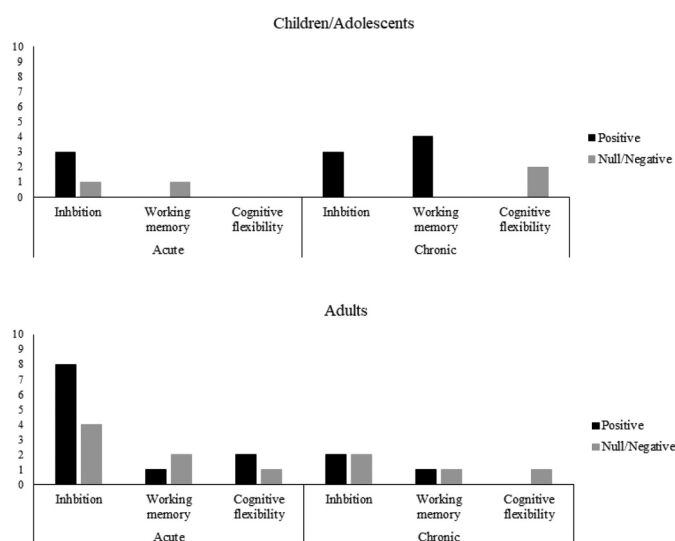


Figure 3. Illustration of intervention effects. Data are presented in children/adolescents (upper panel) and adults (lower panel). Note. Data come from 23 studies, with a total of 39 intervention effects.

of HIIT benefit working memory and cognitive flexibility performance. It is noteworthy that WRR of HIIT may moderate the relation between acute HIIT and inhibition, with a smaller WRR (e.g., 30 second: 30 second) having a positive effect whereas a larger WRR (e.g., 60 second: 30 second) may not (Ludyga et al., 2018). To date, there is no study investigating the moderating role of WRR of HIIT in other subcomponents of executive function (i.e., working memory, cognitive flexibility) or research that modulates the WRR to determine why this factor may moderate the benefits to cognitive outcomes.

In terms of the chronic effects of HIIT, the current evidence suggests that both sprint-based and HICT-based interventions may benefit inhibition and working memory in children (Moreau et al., 2017; Tottori et al., 2019). Moreover, it is possible that children's BDNF profile moderates the effectiveness of HIIT on inhibition and working memory, with BDNF^{met66} carriers benefiting more from HIIT relative to non-carriers (Moreau et al., 2017). This is probably because BDNF^{met66} carriers have higher post-exercise BDNF secretions (Nascimento et al., 2015), which may, in turn, result in stronger neuronal functioning, plasticity, and long-term potentiation (Lipsky & Marini, 2007; Zhou et al., 2011). In contrast, a chronic HIIT program, regardless of the protocol employed, did not benefit cognitive flexibility performance in adolescents (Costigan et al., 2016). However, given there has only been one study delineating this aspect of executive function, more research is needed to verify the findings from Costigan et al. (2016).

Overall, the current evidence relating HIIT and executive function in children and adolescents corroborates the beneficial effects of acute and chronic continuous aerobic exercise (see Kao et al., 2020 for review). Of note, considering that the natural physical activity patterns of children and adolescents are similar to HIIT as well as the time-efficient nature of HIIT allows it to be implemented during shorter periods of time throughout the school day, HIIT-based physical activity may be a viable option in school settings to foster brain health (Lopes et al., 2006).

4.3. Effects of HIIT on adults

In adults, the majority of the data (7 of 11 studies reviewed; Alves et al., 2014; Hashimoto et al., 2018; Kao et al., 2017, 2018; Kujach et al., 2020; Miller et al., 2018; Tsukamoto et al., 2016) supported a positive effect of acute HIIT on inhibition. Findings from three studies (Gmiat et al., 2017; Ligeza et al., 2018; Schwarck et al., 2019) who found null effect of HIIT on inhibition may be confounded by small sample sizes (Gmiat et al., 2017), inappropriate timing of cognitive assessment (Gmiat et al., 2017), prolonged duration of HIIT (Ligeza et al., 2018; Schwarck et al., 2019), and/or sexual dimorphism of participants (Ligeza et al., 2018). Specifically, the sample size of the Gmiat et al. study was relatively small (i.e., 8 young women and 6 middle-aged women), which may have increased the risks of type 2 error. Furthermore, the one-hour interval between exercise cessation and administration of post-intervention inhibition test in the Gmiat et al. study was much longer than other studies assessing inhibition (typically ≤ 30 minutes following exercise cessation; Hashimoto et al., 2018; Kao et al., 2017, 2018; Tsukamoto et al., 2016), and this raises the

possibility that cognitive benefits from exercise may have diminished at the time of cognitive assessment. On the other hand, compared with studies that found improved inhibition following single bouts of HIIT (Kao et al., 2017, 2018), exercise duration in the Ligeza et al. and Schwarck et al. studies are considerably longer (i.e., >25 minutes). A prolonged duration of HIIT may result in overall fatigue, decreased cerebral oxygenation, and/or decompensated levels of blood lactate, which may, in turn, reduce the facilitative effects of HIIT. Another discrepancy that Ligeza et al. and Schwarck et al. studies hold against other findings (Kao et al., 2017, 2018) is related to participants' sexual dimorphism. That is, while the former studies only recruited male participants, the latter studies recruited both men and women. It is plausible that sexual dimorphism may play a moderating role on the magnitude of the effect, as a meta-analysis by Chang et al. (2012) summarizing the effects of acute exercise on cognition indicated that studies with both men and women had larger effect sizes than those studies with either men or women. This moderating role of sexual dimorphism might be accounted for by the fact that men and women have differential secretion of hormones (e.g., dehydroepiandrosterone) relating to arousal (De Menezes et al., 2016) and metabolic responses (Ponjee et al., 1994) following acute exercise, with women showing greater acute exercise-induced secretion (Heaney et al., 2013). Overall, the current evidence supporting the beneficial effect of acute HIIT on inhibition in adults aligns with the effects of single bouts of continuous aerobic exercise (Chang et al., 2012; Hsieh et al., 2018; Kao et al., 2020; Ludyga et al., 2016) and resistance exercise (Chang et al., 2012; Wang et al., 2019), suggesting HIIT may be an alternate means to benefit inhibition during adulthood.

By contrast, there is only a piecemeal of study relating to working memory and cognitive flexibility. While one study favours the positive influence of acute HIIT on working memory in young adults (Gmiat et al., 2017), there are two studies found null (Alves et al., 2014) and negative effect in middle-aged adults (Gmiat et al., 2017). However, considering the high heterogeneity between studies in participants' age (i.e., young adults vs. middle-aged adults), study design (i.e., within-subjects, crossover design vs. within-subjects, pre-test-post-test design), cognitive tasks selected (spatial working memory task vs. verbal working memory task), and/or HIIT protocols (i.e., HICT vs. HIIT), more research is required to clarify if these methodological differences account for the discrepant findings. Likewise, the current findings relating to cognitive flexibility are also controversial, with two studies reporting positive effects in young adults (Dupuy et al., 2018; Kujach et al., 2020) and one study indicating no effect (Schwarck et al., 2019). However, again, these studies differed in terms of study design, HIIT protocols, and/or cognitive tasks employed; thus, it is difficult to draw conclusions regarding the effects of HIIT based on such limited data. Moreover, it is noteworthy that there is no extant data delineating the acute effect of HIIT on older adults' executive function.

With regards to the chronic effects of HIIT on executive function, the available results are mixed. Preliminary data support the positive effect of HIIT on inhibition (De Sousa et al., 2018), indicating that adults with higher compliance to the HIIT protocol (peak in-exercise HR: 184.2 beats.min⁻¹) had larger cognitive gains following training relative to those with lower

compliance (peak in-exercise HR: 170.5 beats.min⁻¹). This finding suggests a moderating role of training fidelity. However, the existing data does not support a positive influence of chronic HIIT on inhibition in older adults (Coetsee & Terblanche, 2017; Kovacevic et al., 2020), which may suggest further contemplation for implementing HIIT protocols in older adults. The current data on other subcomponents of executive function are scarce, with positive effects on working memory found among middle-aged adults (Connolly et al., 2017) but not young adults (Nicolini et al., 2019), and null effects also noted for cognitive flexibility in young adults (Eather et al., 2019). Nevertheless, more research is needed considering that these three studies differ from each other extensively in participants' age, study design, HIIT protocol, and/or training duration (i.e., 6 weeks vs. 8 weeks vs. 12 weeks). In sum, the chronic effects of HIIT on executive function during adulthood remains to be clarified given the small number of studies and high heterogeneity in methodology across the literature.

4.4. Future directions

Given emerging evidence showing a positive effect of HIIT on executive function, there are several potential opportunities for future research. First, since most studies (70%) have assessed the effects of HIIT on inhibition, less is known regarding its effects on working memory and cognitive flexibility, especially in adults (Figure 2). Likewise, more research delineating the chronic effects of HIIT or recruiting middle-aged and older adults are needed. Second, more studies are needed to clarify the dose-response relation between HIIT and different subcomponents of executive function by manipulating WRR. As mentioned earlier, Ludyga et al. (2018) found positive effects of HIIT with smaller WRR but not HIIT with larger WRR. This finding highlights the necessity of clarifying whether different doses of HIIT may lead to different levels of cognitive gain. Third, given that HIIT can be performed in a variety of modalities, including running, cycling, and HICT, it is recommended that future work clarify whether different modalities of HIIT result in similar cognitive changes. In particular, circuit training consists of multi-joint, functional movements (Eddolls et al., 2017), which results in greater muscle recruitment than running/cycling, thereby improving cardiovascular endurance, muscular fitness, and body composition (Heinrich et al., 2015, 2012; Murawska-Cialowicz et al., 2015). It is plausible that the joint benefits in cardiovascular endurance, muscular fitness, and body composition lead to larger cognitive benefits compared to running or cycling as the three health dimensions are all associated with executive function (Hsieh et al., 2016; Kamijo et al., 2012; Kao et al., 2020). To date, there is no study delineating the differential or superior effects of HICT relative to HIIT. Fourth, there is a need to examine the moderating effects of individual differences, such as age (Chang et al., 2012; Ludyga et al., 2016), aerobic fitness (Chang et al., 2012), sexual dimorphism (Chang et al., 2012), genotype (e.g., BDNF^{met66} carriers vs. non-carriers; Moreau et al., 2017), and clinical status (e.g., obesity vs. normal weight), as these factors have been suggested as potential

moderators in the exercise-cognition relationship. Fifth, while the majority of previous studies only employed behavioural measures, there is still a long way to go in exploring the possible mechanisms underlying the relation. Despite several neurophysiological underpinnings (e.g., lactate, BDNF, cortical activation, cerebral oxygenation) proposed by researchers, other endothelial (e.g., VEGF) or endocrinal markers (e.g., irisin, interleukin-6, testosterone, cortisol) with cognitive implications (Carro et al., 2000; Gmiat et al., 2017; Huang et al., 2014; Hung et al., 2018; Tsai et al., 2015; Vital et al., 2014; Voss et al., 2013) should be investigated in future work.

Relative to methodological concerns, it would be useful for future research to include an active control condition, as an inactive comparison may not satisfactorily measure the effectiveness of exercise because it remains unclear whether cognitive gains are a result from locomotion, body composition, or expectations of improvement resulting from participation in a novel intervention (Pontifex et al., 2018, 2019). Moreover, in order to develop ecologically valid interventions, the feasibility of using HIIT programmes for improving executive function in real-world settings should be explored. With the exception of a few long-term studies conducted in schools (Costigan et al., 2016; Leahy et al., 2019), most previous studies have been conducted in laboratories, and thus there are questions about the generalizability of current results.

5. Concluding remarks

While HIIT has been proposed as a time-efficient alternative to traditional exercise, we currently have little knowledge regarding its effects on cognitive and brain health, particularly higher-order executive functions. Results of the current review have supported a positive effect of acute HIIT on the inhibition aspect of executive function in children/adolescents and adults as well as a beneficial effect of chronic HIIT on the inhibition and working memory in children. More research on chronic interventions, focusing on middle-age and older adults, and/or assessing working memory and cognitive flexibility are needed. Future research should also focus on a) using stronger research designs, b) the effects of HIIT dosage/modality, c) consideration of individual differences, d) neurobiological mechanisms underpin the HIIT-executive function relationship, and e) examining the feasibility of different modalities of HIIT in real-world settings.

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ORCID

Ting-Yu Chueh  <http://orcid.org/0000-0003-3624-8465>

Charles H. Hillman  <http://orcid.org/0000-0002-3722-5612>

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